Afforestation using micro-catchment water harvesting system with microphytic crust treatment on semi-arid Loess Plateau: A preliminary result

YANG Xiao-hui[1], WANG Ke-qin[2], WANG Bin-rui[3], YU Chun-tang[1]

[1] *Research Institute of Forestry, Chinese Academy of Forestry, Silvicultural Lab of State Forestry Administration, Beijing 100091, P. R. China*

[2] *Southeast Forestry College, Kunming 650224, P. R. China*

[3] *College of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, P. R. China*

Abstract: Water harvesting is one of main measures to solve water shortage resulting from less precipitation and erratically seasonal distribution in arid and semi-arid areas. Different types of anti-infiltration treatments including mechanical and chemical to micro-catchment and their runoff efficiencies had been reported. This paper, through 5 years experiment from 1992 to 1996, is aimed at studying the impacts of microcatchment water-harvesting system (MCWHS) with microphytic crust treatment on afforestation on semi-arid Loess Plateau. The results showed that after 3 years of crust inoculation, crust had covered majority of MCWHS and the function of water harvesting had also been demonstrated partially, there were significant difference in soil moisture of shallow soil layer in three typical spring stages between crust cover and control treatments (0.05 level), and about 0.9%-6.04% increase of monthly mean soil moisture within 1m soil layer in spring of late 3 years. The impact of severe spring drought can be alleviated effectively. In the meanwhile, as crust developed on the treated surface, there are significant differences (0.05 level) for tree height (H), diameter at breast height (DBH) and diameter at ground level (DGL) at the end of the study period (1996) with the increases by 22.38%, 17.34%, and 20.49% respectively compared with the control treatment. Microphytic crust, as one of biological infiltration-proof materials, may become the optimized option for revegetation in Chinese Great West Development Strategy due to its self-propagation, non-pollution to water qualities, long use duration and relatively cost effective. Further work should be focused on the selection of endemic crust species and their batch-culture in arid environment.

Keywords: Afforestation; Microphytic crust; MCWHS; Soil moisture; Semi-arid Loess Plateau

CLC number: S728.2 **Document Code**: A **Article ID**: 1007-662X(2005)01-0009-06

Introduction

Water harvesting has been widely used for agriculture, forestry, rangeland management, and living water supply in arid climate all over the world over 4 000 years (*e.g.* Evenari *et al.* 1961; Mehdizadeh *et al.* 1978; Fraiser 1980; Sharma, *et al.* 1986; Fox & Rockstrom 2000). As Boers and Ben-Asher (1982) overviewed, the definition of water harvesting was based on three characteristics as arid and semi-arid climate, local water, and small-scale operation, and three elements as runoff inducement, runoff collection, and storage and conservation. The often-used runoff inducement methods include (1) undisturbed natural surface such as sandstone rock slopes, slick rock hillsides or granite outcrop, (2) surface mechanic treatment such as rock clearing, smoothing and compacting, which was usually combined with vegetation clearing, and (3) surface chemical treatment such as sodium salts, paraffin wax, and asphalt. It was no doubt that surface chemical treatments could increase runoff efficiency to some extent (Mehdizadeh *et al.* 1978; Fink *et al.* 1980; Frasier 1980; Boers *et al.* 1982). However, the most of treatment cost was very expensive (Emmerich *et al* 1987), what is more, these chemical materials are difficult to get somewhere, and pollute soil and be harmful to plants less or more. So a kind of cheap and easy-to-get infiltration-preventing material is necessary urgently for ecological-based water harvesting.

Recently, microphytic crust has been drawing more attention from researchers, and many literatures reported that microphytic crust exists in different soil types such as loess and dune sand in arid and semi-arid areas all over the world and plays a significant role in arid ecosystem (West 1991; Eldridge & Greene 1994). Hydrologically, semi-permeable microphytic crust reduces rain infiltration and therefore increases runoff on one hand (Brotherson and Rushforth 1983; Yair 1990; Kidron and Yair 1997), and on the other hand, protects soil surface from erosion and soil moisture from evaporation (Chartres and Mucher 1989; Kinnel *et al.* 1990). Meanwhile microphytic crust characterized by self-propagation, non-pollution to water qualities and cost effective, all of which increase technical and economic feasibility of microphytic crust as the inducement materials of runoff in arid and semi-arid areas.

In China, there has been also a long history to use different rainwater collection system for dryland agriculture (Li *et al.* 2000, 2001). Until recent years, some successful cases of water harvesting for afforestation on the semi-arid and arid Loess Plateau were reported (Wang *et. al.* 1996). The Loess Plateau is now famous for its severe soil erosion due mainly to scarce vegetation, arid climate and erratic intra-annual rainfall variation, compared with the former ancient prosperous civilization (ISTLP-CAS 1991). Revegetation has been a tedious task for the environmental improvement and poverty alleviation in this region. Irrigation is almost impossible to vegetation recovery constrained by local condition, and hence vegetation growth depends solely on low and erratic precipitation. However, as a result of high initial plantation density, soil water was over-used by vegetation and

Foundation item: This paper was supported by National Natural Science Foundation of China (No.30171205)

Biography: YANG Xiao-hui (1968-), male, Ph.D. in Research Institute of Forestry, Chinese Academy of Forestry Beijing 100091, P. R. China. E-mail: yangxh@forestry.ac.cn.

Received date: 2004-10-25

Responsible editor: Song Funan

soil dried layer formed, which influenced seriously normal vegetation growth (Yang 1996, Wang *et al.* 2001). Hence water harvesting techniques are becoming a premier way for overcoming the soil dessication and enhancing vegetation rehabilitation (Wang *et al.* 1996, Wang & Wang 1998).

There are different types of microphytic crust distributed on Loess Plateau (Wang *et al.* 1996), which provides basic material for this experiment. This paper aimed to study the five-year effect of microphytic crust inoculation to micro-catchment on (a) soil moisture dynamics within the infiltration basin, (b) soil water change in early spring, and (c) growth analysis of individual tree in infiltration basin. This study will be instrumental in better understanding the role of microphytic crust in the micro-catchment water harvesting system (MCWHS), and attempts a new alternative in revegetation on semi-arid Loess Plateau.

Materials and methods

Study site

The study site is located in the north of semi-arid Loess Plateau, a part of the loess gully-hilly area in the middle reaches of Yellow River (37°36′58″N, 110°02′55″E), China, with a average altitude of 1 200 m (Fig.1), and belongs to Yukou Town, Fangshan County, Shanxi Province. The climate is typical continent monsoon type, and annual mean precipitation is 416 mm, of which precipitation from June to August is more than 70% of annual precipitation, annual maximum and minimum of air temperature are 35.6℃ (29, May 1980) and -25.3℃ (30, January 1980), respectively, and aridity index and annual frost-free days are 1.3 and 140 days, respectively. The soil type is loessial soil with a pH of 8.0-8.4. Vegetation type is forest-bush steppe, and vegetation is sparse in study area, including several shrub species such as *Rosa xanthina*, *Ulmus macrocarpa* and *Ostryopsis davidiana*, and herbaceous plants such as *Artemisia sacrorum*, *A. orietatis*, *A. epigejos*, *A. subdigitata*, *Agropyron cristatum*, *Setaria lutescens*, *Pennisetum glaceidum* and *Patentilla discolor*.

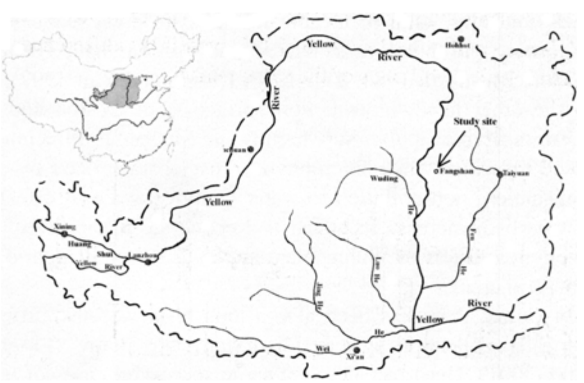

Fig.1 The location map of Loess Plateau and study site

Materials

Black Locust (*Robinia pseudoacacia*), a worldwide distributed tree species characterized by its strong habitat suitability and multi-purpose value (Keresztesi 1988), is dominant afforesting tree species on the semi-arid Loess Plateau (Wang & Xue 1994), moreover which has better conservation function of soil and water and good quality as mine prop material in the north part of China (Bi 1995). Its growth in this area is also water-limited (Yuan *et al.* 1996), and water harvesting with different micro-catchment surface treatment promotes the growth of locust (Wang *et al.* 1996; Wang & Wang 1998).

Microphytic crust can be found everywhere in the study site and is named as "black crust" by the local people. The crust consists mostly of lichen where *Endocarpon pusillum* Hedw is the dominant species (Wang *et al.* 1996).

Methods

The micro-catchment water harvesting system (MCWHS) consists of micro-catchment (MC), infiltration belt (IB), and individual tree (IT) planted in IB (Fig. 2). The micro-catchment was prepared in the fall of 1991, on which vegetation was removed and soil surface was compacted and smoothed, the fragment of microphytic crust was collected in the study site and crumbled in laboratory, and then the crust slurry was sprayed evenly to inoculate on the treated slope with suitable humidity and temperature in continuous cloudy or rainy days. The same-size undisturbed MC was kept as control treatment, and 30 MCWHSs for each treatment were separately prepared. Soil in IB was prepared and vegetation cleared from MC is minced and added into soil as green manure. One-year-old seedlings of black locust (*Robinia pseudoacacia*) with two-year-old root system were transplanted from nursery to IB in spring of 1992. The survival rates of seedling were 86.67% and 90% for crust cover treatment and control treatment in early spring of 1993, respectively, therefore, 25 trees for each treatment were selected for comparison study.

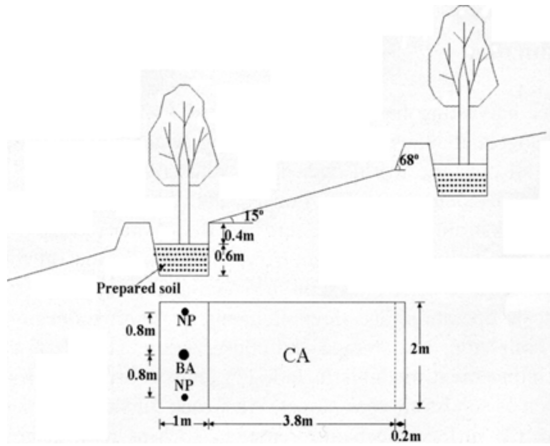

Fig. 2 Schematic micro-catchment water-harvesting system

The rainfall amount was measured with recording rain gauge installed within the study site. Some research results showed that the roots of black locust on the Loess Plateau mostly distributed within 1-m deep soil layer (more than 90%) (Li *et al.* 2002, 2004). Soil moisture within a depth of 100 cm in the IB was measured with 10 days and an interval of 20 cm from the spring of 1992 using neutron probe (NP), and the growth parameters including height (H), diameter at breast height (DBH) and diameter at ground level (DGL) were also measured at each end of the growth period. In order to clarify the role of crust cover treatment in alleviating drought in spring, three typical stages in spring, *i.e.* the first stage (before tree germination), the second

stage (during tree germination), and the third stage (after tree germination), were determined to compare the differences in soil moisture in five consecutive soil layers. During the experimental period, all human disturbances were removed except the routine observation, though some wild herbivores such as rabbits moved in the whole experimental sites, no obvious damage to MCs was found.

Data were analyzed for significance by an unpaired Student's t test for comparing soil moisture in growth seasons and in spring of each year, and tree growth parameters (H, DBH and DGL) between microphytic crust cover and control plots. Probabilities of less than 0.05 were considered as statistically significant. SPSS software was selected as the statistical tool (SPSS 1999).

Results and discussion

Crust development

The microphytic crust developed gradually on the micro-catchment surface (Table 1). It was noteworthy that in the rainfall season of 1995, some mosses mostly consisting of *Didymodon tectorum* (C. Muel.) Saito came to colonize on the crust community and green the crust cover, and in the autumn of 1995, a matted layer of 0.8-1.0 millimeter with underlying soil was formed by scalping surveys and the whole micro-catchment was almost covered by crust. The soil surface compactness measured for micro-catchment is 25-40 kg·cm^{-3}.

Table 1. The rainfall amount and description of microphytic crust treatment during 1992-1996

Year	Rainfall (mm)	Micro-morphological description
1992	373.4	Loess soil matrix dotted with crust mini-patches, crust cover rate less than 30%
1993	347.6	Mosaic between bare soil and crust, crust cover rate is about 70%
1994	368.1	Crust almost covers soil surface, crust cover rate more than 90%
1995	414.3	Mosses colonize on crust community, green color dotted on crust
1996	433.2	Green mat-like layer appeared

Soil water change in early spring

Total rainfalls in growing seasons from 1992 to 1996 (April to October) were 373.4 mm, 347.6 mm, 368.1 mm, 414.32 mm, and 433.2 mm, respectively (Fig. 3), in which the sums of April and May are 23.4 mm (6.27%), 17.1 mm (4.92%), 34.8 mm (9.45%), 58.65 mm (14.16%), and 13.9 mm (3.21%), respectively, all of them is less than 15% of the total in growing seasons, showing that spring drought was a key factor influencing plant growth. There were no significant difference for monthly mean soil moisture within 1-m deep soil layer between control treatment and crust cover treatment, but in the springs (April to June) of the late 3 years, there were separately increases by 0.9%-3.72%, 0.91%-4.72%, and 1.40%-6.04% for crust cover treatment compared with control treatment (Fig. 3). The significance analysis of soil moisture dynamics within 1-m deep soil layer for three spring stages in 5 consecutive years shows that there are no significant differences in soil moisture for all the soil layers in three spring stages of 1992, 1993, and 1994 (Fig.4 (a1-c2)) except the stage after tree germination in 1994, in which existed in significant difference in a soil layer of 0-20 cm between two treatments (Fig.4 (c3)). In 1995, significant differences appeared in the soil layers of 0-20 cm and 20-40 cm for the first stage and in soil layers of 0-20 cm, 20-40 cm and 40-60 cm for the second stage, respectively (Fig.4 (a4 and b4)), while no significant difference existed in the third stage (Fig.4 (c4)). In 1996, there are significant differences in soil layers of 0-20 cm and 20-40 cm for all the three stages (Fig.4 (a5, b5 and c5)). Obviously, as the development of crust on the surface of micro-catchment, runoff coefficient gradually increases, and more and more runoff is collected into the infiltration belt, especially in autumn. Collected water cannot consumed totally for effective tree transpiration and ineffective soil evaporation, and surplus water stored in the shallow soil layer of infiltration belt, which is very precious for the tree germination and growth in next spring, hence the differences of soil moisture in shallow soil layer are significant. However, the rainfall amount in the antecedent autumn and consumption by evapotranspiration may influence the soil moisture dynamics in the spring significantly. For example, there is no significant difference in the third stage of 1995 even if the differences exist in the former two stages of the same period.

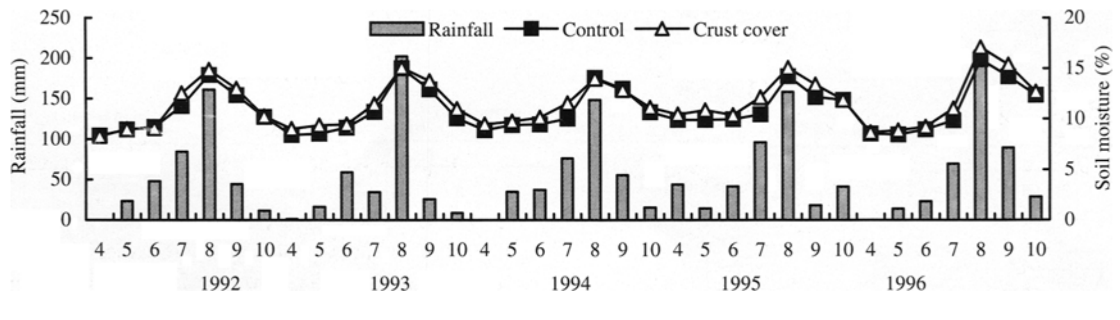

Fig. 3 Monthly rainfall and monthly mean soil moisture for control and crust cover treatments from 1992 to 1996

As a shallow-root tree species without main root system, though black locust develops deep-root feature on Loess Plateau (Li *et al.* 2002b; Zhao *et al.* 2004), the fine root (diameter less than 1 mm) mainly concentrated within 1-m deep soil layer, for example, the length of fine root for 10-year-old black locust within soil layers of 0.4 m and 0.7 m separately account for 58.54% and 87.63% of those within 1-m deep soil layer on average, and their biomass account for 62.33% and 86.84%, respectively (Zhao *et al.* 2004). Obviously, the change of soil moisture within 1-m deep soil layer, especially in soil surface layer (0-40 cm), have great contribution to tree growth in early spring.

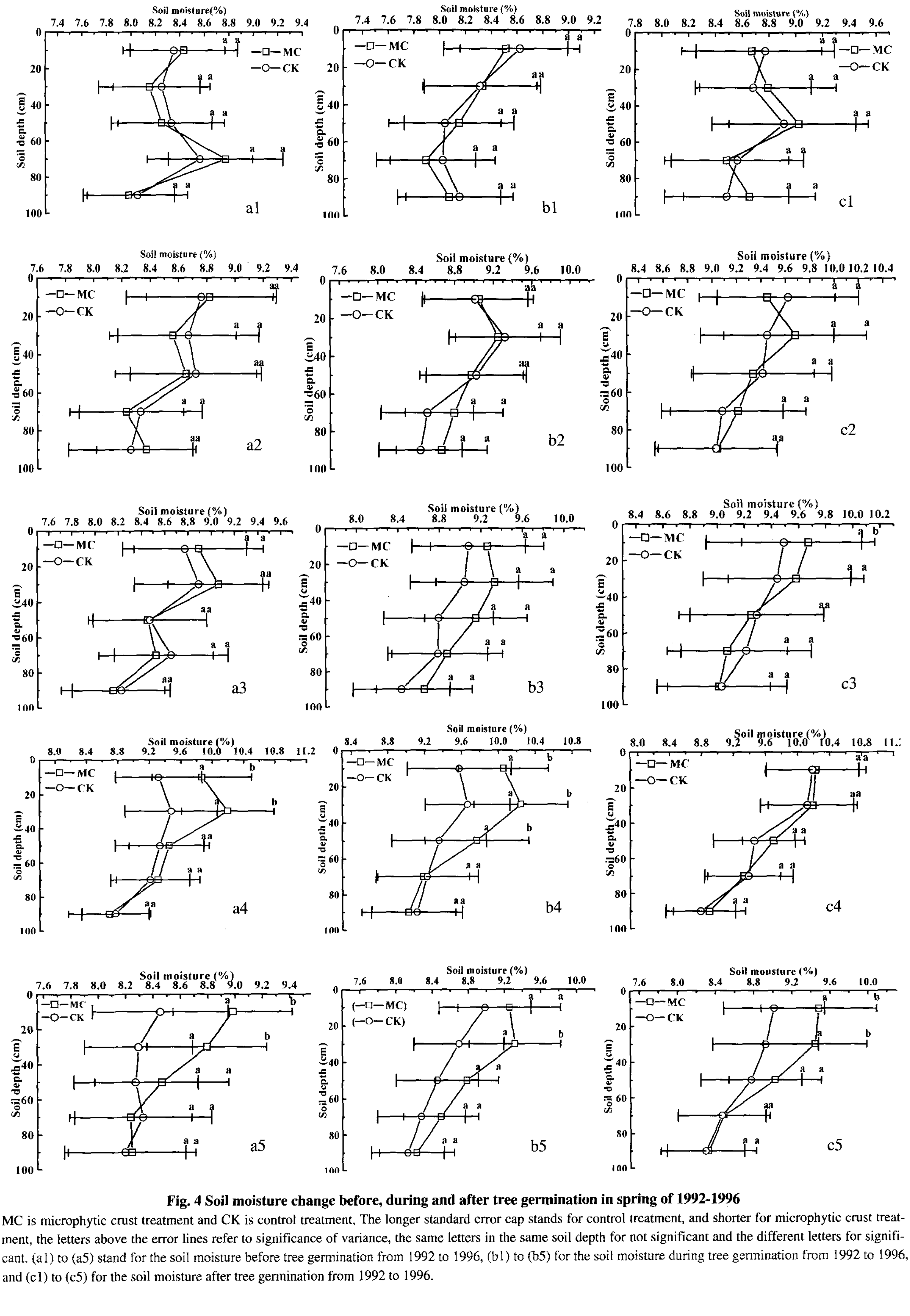

Fig. 4 Soil moisture change before, during and after tree germination in spring of 1992-1996

MC is microphytic crust treatment and CK is control treatment. The longer standard error cap stands for control treatment, and shorter for microphytic crust treatment, the letters above the error lines refer to significance of variance, the same letters in the same soil depth for not significant and the different letters for significant. (a1) to (a5) stand for the soil moisture before tree germination from 1992 to 1996, (b1) to (b5) for the soil moisture during tree germination from 1992 to 1996, and (c1) to (c5) for the soil moisture after tree germination from 1992 to 1996.

Tree growth analysis

In the 5 years observation, the tree height (H), diameter at breast height (DBH), and diameter at ground level (DGL) for crust treatment were larger to some extent than those for control treatment (Fig. 5). At the end of study period (October of 1996), H, DBH, and DGL for crust cover treatment were 6.78 m, 5.21 cm, and 6.82 cm, respectively, increasing by 22.38%, 17.34%, and 20.49% compared with the control treatment. The *t* test for these three growth parameters during 1992-1996 showed that the significant differences appeared in 1996, 1995-1996 and 1995-1996 for H, DBH and DGL, respectively, which gave the most direct evidence that more water was available in IB and trees could grow faster as crust developed on the crust cover treatment compared with the control treatment. Due to measurement errors and possible sapling shoot-shriveling in spring drought, the difference for H is less significant than those for DBH and DGL.

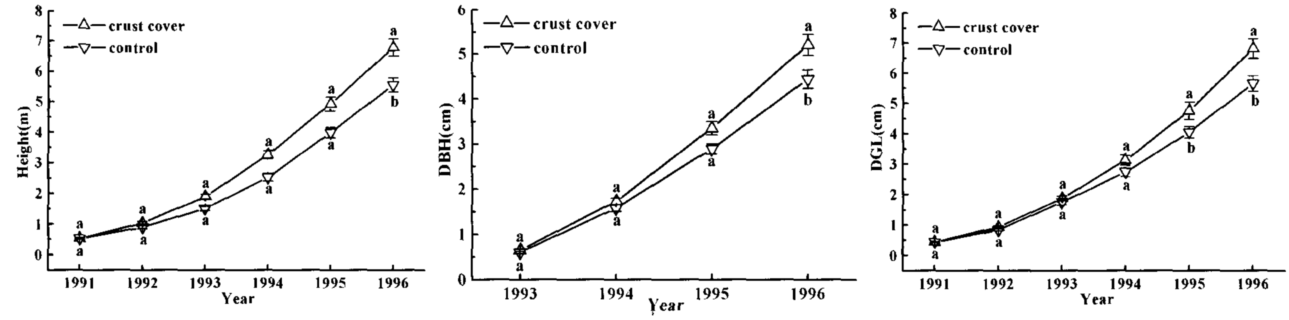

Fig. 5 Mean annual tree height, diameter at breast height and diameter at ground level for crust cover and control surface treatments

Lines represent the mean ± SE, and letters near the error lines indicate difference of significance at 0.05 level (in the same year, the different letters for significant and the same letters for no significant)

Implications and conclusion

Undoubtedly, in arid and semi-arid areas, the increase of the ratio of MC area to IB area does increase runoff amount and improve soil water environment for plant growth, even if MC surface is kept undisturbed. Of course, runoff efficiency is determined by micro-topography, rainfall properties, and water infiltration rate. In the loess hilly-gully area, trees are usually planted on the slope, hence only through the reduction of initial plantation density (*i.e.* increase of MC area) could the water harvesting effects be gotten (Wang and Wang 2000). As for effect of microphytic crust on infiltration or runoff, conflicting results are at first difficult to explain, some concluded that crust can increased water infiltration (Gifford 1972; Clair and Johansen 1990), while others agreed that crust did decrease infiltration (Brotherson and Rushforth 1983; Yair 1990). The differences in infiltration may result from different crust composition, antecedent moisture status of the crusts, individual rainfall properties or effects of crusts on micro-topography (Eldridge and Greence 1994). However it has been proved that, combined with slope, crust cover can indeed increase runoff (Li *et al.* 2002). In loess gully-hilly area, the majority of afforestation was conducted on sloping land, and crust cover should increase the runoff coefficient theoretically, in practice, the moisture environment within infiltration area and tree growth condition in this study gives further agreement to this viewpoint.

The recovery rate of microphytic crust is a key factor influencing water-harvesting efficiency in this study. A complete recovery of a well-developed crust after disturbance such as fire or trampling needed 15 years (Anderson *et al.* 1982). The algal crust might recover in 5-9 years under favorable climatic conditions (Johansen *et al.* 1984). Clair *et al.* (1986), evaluating algal establishment inoculating with soil crust slurry on fire-disturbed site, found that six blue-green algae species along with one lichen species in crust-slurry-treated plots were significantly greater number. In this study, lichen crusts were collected and inoculated on the smoothed slope and recovery conditions of crust were also observed in the experiment. The experimental results showed that after 3 years, crust had covered majority of MCWHS and moss species were becoming colonizers, the function of water harvesting had also demonstrated partially, a part of water collected in last autumn can be used in dry spring, which alleviate the influence of spring drought effectively, and the water collected in the whole growth period significantly increases the tree growth compared with the control treatment. However, this method seems not extensible broadly on the semi-arid Loess Plateau, because the collection of sufficient soil crust as inoculum will destroy the soil surface cover elsewhere and result in new soil erosion, hence, batch-cultures of selected blue-green algae species could easily be produced in the laboratory.

In addition, it is obvious that efficiency of water harvesting of MC with mechanic or chemical treatments will decrease as the period of use increases, while that with crust cover will increase gradually with the development of crust, which will be helpful to solve the main conflict between tree growth and the efficiency of water harvesting in past micro-catchment design and to the extent meet increasing water moisture requirement of tree growth.

In a word, water-harvesting techniques have broadly perspective in dryland development. The experimental data proved crust treatment can increase runoff efficiency, which contributes more water to tree's growth in the whole growing period, what's more, water stored within shallow soil layer in last autumn can mitigate spring drought to some extent in next year and increase tree growth markedly. Further work should be focused on the selection of endemic crust species and their batch-culture in arid environment and WUE of trees for harvested water. Microphytic crust, as one of biological infiltration-proof materials, may become the optimized option for revegetation in Chinese Great West Development Strategy owing to its special natures.

Acknowledgements

We thank associate professor Zhang Kebin for his warm-hearted help during this article accomplishment, and thanks are

also extended to Professor Wang Baitian and Professor Zhang Fu-e for their help in the field experiments and constructive proposals for experimental design.

References

Anderson, D.C., Harper, K.T., Rushforth, S.R. 1982. Recovery of cryptogamic soil crusts from grazing on Utah winter ranges [J]. J. Range Manage., **35**: 355–359.

Bi, J. 1995. Multi-purpose management of Black Locust [M]. Beijing: China Forestry Publishers, p3–10. (in Chinese)

Boers, T.M., Ben-Asher, J. 1982. A review of rainwater harvesting [J]. Agric. Water Manage., **5**: 145–158.

Brotherson, J.D., Rushforth, S.R. 1983. Influence of cryptogamic crusts on moisture relationships of soil in Navajo National Monument Arizona [J]. Great Basin Naturalist, **43**: 73–78.

Chartres, C.J., Mucher, H.J. 1989. The response of burnt and unburnt rangeland soil surfaces to simulated raindrop impact and water erosion [J]. Earth Surface Processes and Landforms, **14**: 407–417.

Eldridge, D.J., Greene, R.S.B. 1994. Microbiotic soil crusts: a review of their roles in soil and ecological processes in the rangelands of Australia [J]. Australian Journal of Soil Research, **32**: 389–415.

Emmerich, W.E., Frasier, G.W., Fink, D.H. 1987. Relation between soil properties and effectiveness of low-cost water-harvesting treatments [J]. Soil Sci. Am. J., **51**: 213–219.

Evenari, M.L., Shanan, L., Tadmor, N.H. 1971. The Negev: The challenge of a desert [M], Cambridge: Harvard University Press, MA.

Fink, D.H., Frasier, G.W., Cooley, K.R. 1980. Water harvesting by wax-treated soil surfaces: progress, problems and potential [J]. Agric. Water Manage., **3**: 125–134.

Fox, P., Rockstrom, J. 2000. Water-harvesting for supplementary irrigation of cereal crops to overcome intra-seasonal dry-spells in the Sahel [J], Phys. Chem. Earth (B), **25**: 289–296.

Frasier, G.W. 1980. Water harvesting for livestock, wildlife and domestic uses [J]. J. Soil Water Conserv., **35**: 125–128.

Gifford. G.F. 1972. Infiltration rate and sediment production on a ploughed big sagebrush site [J]. Journal of Range Management, **25**: 53–55.

Integrated Survey Team of Loess Plateau, Chinese Academy of Sciences (ISTLP-CAS) (Ed). 1991. Regional soil erosion features and control measures on the Loess Plateau [M]. Beijing: Chinese Sci & Tech Publisher.p12 - 15. (in Chinese)

Johansen, J.R., St. Clair, L.L., Webb, B.L., *et al.* 1984. Recovery patterns of cryptogamic soil crusts in desert rangelands following fire disturbance [J]. The Bryologist, **87**: 238–243.

Keresztesi, B. (Ed), 1988. The black locust [M]. Akademiai Kiado, Budapest, p196.

Kidron, G.J. Yair, A. 1997. Rainfall-runoff relationship over encrusted dune surfaces, Nizzana, Western Negev, Israel [J]. Earth Surface Processes and Landforms, **22**: 1169–1184.

Kinnel, P.I.A., Chartres, C.J., Watson, C.L. 1990. The effect of fire on the soil in a degraded semi-arid woodland. II. Susceptibility of the soil to erosion by shallow rain-impacted flow [J]. Aust. J. Soil Res., **28**: 779–794.

Li, F.R., Cook, S., Geballe, G.T., *et al.* 2000. Rainwater harvesting agriculture-- an integrated system fro water management on rained land in China's semiarid areas [J]. AMBIO, **29**: 477–483.

Li, P., Zhao, Z., Li, Z.B., *et al.* 2002. Research on root distribution parameters of *Robinia pseudoacacia* on different sites in Chunhua County [J]. Journal of Nanjing Forestry University (Natural Sciences Edition), **26**(5):33–36. (in Chinese)

Li, P., Zhao, Z., Li, Z.B., 2004, Vertical root distribution characters of *Robinia pseudoacacia* on the Loess Plateau in China [J]. Journal of Forestry Research, **15**(2): 87–92.

Li, X.Y., Gong, J.D., Gao, Q.Z., *et al.* 2001. Incorporation of ridge and furrow method of rainfall harvesting with mulch for crop production under semi-arid conditions [J]. Agri. Water Manage., **50**: 173–183.

Mehdizadeh, P., Kowar, A., Vaziri, E., *et al.* 1978. Water harvesting for afforestation, I. Efficiency and life span of asphalt cover [J]. Soil Sci. Am. J., **42**: 644–649.

Sharma, K.D., Pareek, O.P., Singh, H.P. 1986. Micro-catchment water harvesting for raising jujube orchards in an arid climate [J]. Trans. Am. Soc. Agric. Eng., **29**: 112–118.

SPSS Inc. 1999. SPSS for Windows 10.0 [C]. Chicago, Illinois.

St. Clair, L.L., Johansen, J.R. 1993. Introduction to the symposium on soil crust communities [J]. Great Basin Naturalist, **53**: 1–4.

Veste, M., Littmann,T., Breckle, S.W., *et al.* 2001, The role of biological soil crusts on desert sand dunes in the northwestern Negev, Israel [C], In: Breckle, S.-W., Veste, M. and Wucherer, W. (eds). Sustainable land use in deserts. Berlin: Springer-Verlag, pp357–367.

Wang, L., Shao, M.G., Hou, Q.C., *et al.* 2001. The analysis to dried soil layer of artificial *Robinnia pseudoscacia* forestry land in the Yan'an experimental area [J]. Acta Bot. Boreal. -Occident. Sin., **21**: 101–106. (in Chinese)

Wang, B.R. and Wang, B.T. 1996. Runoff forestry on the Loess Plateau [M]. Beijing: China Forestry Publishing House. p21 - 25. (in Chinese)

Wang, K.Q, Wang, B.R. 1998. The initial studies of afforestation by water-harvesting to prevent soil desiccation of artificial plantation [J]. Scientia Silvae Sinicae, **34**: 14–21. (in Chinese)

Wang, K.Q., Wang, B.R. 2000. Study on water productivity of the stands afforested by water harvesting techniques [J]. Scientia Silvae Sinicae, **36**(supp.1): 1–9. (in Chinese)

Wang, Z.L., Xue, Z.D. 1994. Ecological division of suitable growing area of *Robinia Pseudoacacia* forest on Loess Plateau [J]. Research of Soil and Water Conservation, **1**: 43–47. (in Chinese)

West, N.E. 1990. Structure and function of microphytic soil crusts in wildland ecosystems of arid to semiarid regions [J]. Advances in Ecological Research, **20**: 179–223.

Yair, A. 1990. Runoff generation in a sandy area-the Nizzana sands, western Negev, Israel [J]. Earth Surface Processes and landforms, **15**: 597–609.

Yang, W.X. 1996. The preliminary discussion on soil desiccation of artificial vegetation in the northern regions of China [J]. Scientia Silvae Sinicae, **32**: 78–85. (in Chinese)

Yuan, Y., Hui, Y.Y., Wu, Y.L., *et al.* 1996. Influence factors of black locust growth on the Loess Hilly region [J]. Research of Soil and Water Conservation, **3**: 146–154. (in Chinese)

Zhao, Z., Li, P., Xue, W.P., *et al.* 2004. Study on relations of growth and vertical distribution of fine root system of main planting tree species to soil density in the Weibei Loess Plateau [J]. Scientia Silvae Sinicae, **40**(5):50–55. (in Chinese)